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Award Number: W81XWH-04-1-0034

TITLE: Enhanced Ultrasound Visualization of Brachytherapy Seeds by a Novel Magnetically Induced Motion Imaging Method

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REPORT DATE: April 2005

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2005	Annual (1 Apr 2004 - 31 Mar 2005)

4. TITLE AND SUBTITLE
Enhanced Ultrasound Visualization of Brachytherapy Seeds by a Novel Magnetically Induced Motion Imaging Method

5. FUNDING NUMBERS
W81XWH-04-1-0034

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 Words)

We report our progress in developing Magnetically Induced Motion Imaging (MIMI) for unambiguous identification and localization brachytherapy seeds in ultrasound images. We report initial results from our finite-element model which provides an estimate of the torque required for a given seed displacement (55μm per μNm) and an optimum seed vibration frequency of 310Hz. We have determined that the tissue vibration isosurfaces shrink with increasing frequency and have developed tools to measure these. Major results are the development of a finite-element model of a brachytherapy seed embedded in tissue, and the development of Matlab code to simulate the ultrasound echoes arising from tissue motion extracted from the finite-element model.

14. SUBJECT TERMS
Prostate Cancer

15. NUMBER OF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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Introduction:

We have devised a method called Magnetically Induced Motion Imaging (MIMI) for identifying brachytherapy seeds in ultrasound images. Ultrasound guided brachytherapy [Holm1983, Nag1997] is a common treatment for prostate cancer. The overall goal of this project is the unambiguous identification and accurate localization of brachytherapy seeds with ultrasound. Accurate determination of seed location is critical in delivering the correct dose distribution to the prostate. Automatic seed segmentation and real-time dose planning are enabled by this technique. Furthermore, the technique enables ultrasound to replace CT for post-implant evaluation, by providing a mechanism by which implanted seeds may be reliably identified by ultrasound. The proposed research will investigate and optimize the materials, instrumentation and algorithms for MIMI, to develop simulation, analytic and phantom methods to explore the relevant phenomena, and to conduct clinically realistic evaluations of the method.

Body:

This report documents activities related to this grant for the period of April 1 2004 to June 30 2004. Work on this grant was halted and all expenditures stopped at the end of June 2004 as a result of the transfer of the PI, Stephen McAleavey, from Duke University to the University of Rochester. No grant money has been spent since June while the transfer has been in progress. Nevertheless, progress has been made in the short time the project was active.

The Statement of Work identifies the following tasks:

Task 1. Modeling of seed electromechanics (Months 1-18)
- A) Propose magnetic core geometry
- B) Develop finite-element model of magnetic seed core for electromagnetic simulation
- C) Solve for seed forces as a function of field strength, orientation and gradient
- D) Iteratively modify core design to maximize induced force given a constant-volume constraint

Task 2. Modeling of seed-tissue mechanics (Months 6-24)
- A) Develop finite-element mesh of seed and tissue
- B) Solve for steady-state vibration amplitude over 50-500Hz band
- C) Calculate vibration amplitude of seed vs. frequency
- D) Find iso-amplitude contours within tissue as a function of vibration frequency

Task 3. Seed detection algorithm development (Months 12-36)
- A) Simulate ultrasound RF echoes from seed and tissue vibrating as determined in Task 2 for varying seed-beam angle
- B) Evaluate motion detection and clutter suppression methods
- C) Determine vibration frequency which provides maximum spatial resolution

Task 4. In-vitro implementation (12-36)
- A) Fabricate or procure model seeds based on core design developed in Task 1
- B) Procure prostate phantom
- C) Implant seeds and clutter targets in prostate phantom
- D) Capture RF echo data and generate seed images using the algorithm of Task 3
- E) Implant seeds in excised animal tissue samples and image using the algorithm of Task 3

The greatest progress has been made on Task 2. We have developed a finite-element model (Figure 1) for a seed embedded in tissue and calculated the response to a sinusoidally varying torque on the seed. Tissue is modeled as a viscoelastic solid, where the shear modulus G is time dependent

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t}$$

where G_0 is 670Pa, G_∞ is 67, and β is 100μs. A 50kPa bulk modulus and a density of 1g/cm^3 was applied for the tissue. The seed is modeled as a rigid bar with a density of 10g/cm^3. The mesh is 37.5 x 25 x 10 mm with an isotropic element size of 0.375mm.

We have found a mild resonance (Q of approximately 1.7) in the seed-tissue system with a resonance frequency of approximately 310Hz. Figure 2 shows the displacement vs. frequency calculated for a seed embedded in tissue. The scaling factor to convert applied torque to displacement is 55μm per μNm torque at 300Hz. We plan to expand the range of tissue parameters involved in the simulation (shear modulus, loss) and frequencies calculated.

Code for simulating the received echo required to accomplish Task 3 has been written in Matlab and tested. A uniform scattering phantom is represented as a list of randomly positioned point targets of equal echogenicity. These points are uniformly distributed within a specified volume, with a density of 10 scatterers per resolution cell. These point locations are taken as the initial, pre-displacement scatterer positions. Displacement vector field data from the finite-element simulations are used to reposition the scatterers at several (3-10) time steps within a vibration cycle. For each scatterer in the phantom, the eight surrounding mesh points are determined. The displacement components of the scatterer are linearly interpolated from the displacement vectors at each mesh point. Scatterer motion in all three dimensions is simulated.

A simulated RF ultrasound echo is generated at each FEM timestep using Field II, a linear acoustic scattering simulator [Jensen]. An Siemens Antares VF10-5 probe is modeled as the imaging transducer. We are developing a model for the EC9-4 endocavity transducer, a better model for a transrectal probe. At each timestep, scanning of the repositioned scatterers is simulated to produce a synthetic RF signal. The process is repeated for every time step in the finite-element simulation.

It should be noted that this code has proven useful in other research. In particular, it was adapted and applied to ARFI imaging simulation [Palmeri].

No significant progress was made with respect to Task 4. This is expected however, as its planned time for execution falls outside of the time frame of this report. We have obtained the materials required for phantoms and test seeds but have not yet fabricated these items. Progress with respect to Task 1 is limited to the selection of appropriate finite-element software (FEMLAB) and determination of an analytical model for forces on a cylindrical seed [Jones1995] for verification of finite-element model results.

Key Research Accomplishments:

- Finite-element model of seed in tissue
- Code – FEM output to simulated RF ultrasound echo

Reportable Outcomes:

While not strictly within the scope of this grant, code developed for modeling the echo from tissue was adapted to generate model data for [Palmeri2005].

Conclusions:

This report has described the groundwork performed for execution of this grant over a three-month period. The important results are the development of finite element models for simulation of seed/tissue mechanics, and Matlab code for simulation of ultrasound RF echo data from vibrating seeds embedded in tissue. These two tools are central to the development of optimized seed excitation and signal processing techniques that are to follow in this grant.

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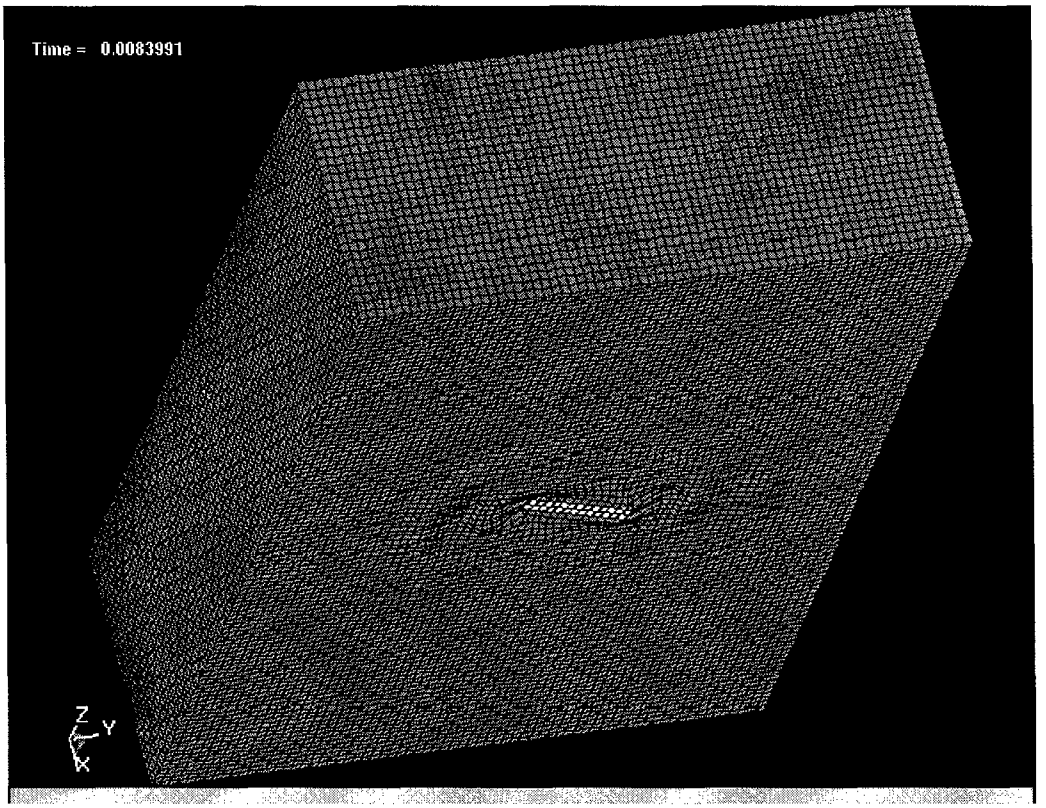

Figure 1. Finite element mesh of seed in tissue. The mesh is 37.5 x 25 x 10mm. Tissue is modeled as a viscoelasatic solid with a 50kPa bulk modulus. Simulations have been run at 50, 300 and 400 Hz.

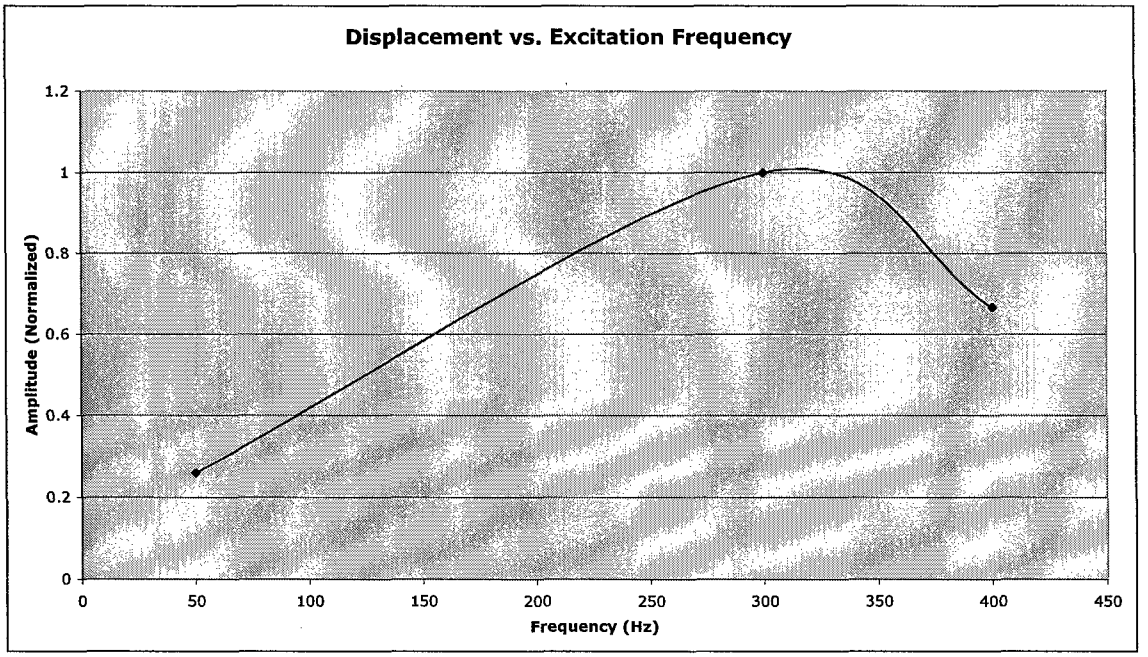

Figure 2. Frequency response of tissue to seed vibration. Peak displacement amplitude occurs at 310Hz. The Q of the system is approximately 1.7. Displacement amplitude of 55microns at 300Hz is obtained for a 1 micro-Nm input torque.